Physical Removal of Ablated Aluminum with Titanium Scraper

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Abstract

A railgun is a high velocity launcher which relies on the Lorenz force to accelerate projectiles commonly made of aluminum. When a railgun is fired, the large current required to accelerate the projectile to high speeds causes a portion of the armature's contacting surface to ablate onto copper rails with the largest concentration located at the startup region. This ablation impedes the path of fired armatures causing deformation of subsequent armatures. In addition, aluminum buildup can hasten the rate of rail wear by increasing the incidence of voltage spikes due to poor continuity as well as high velocity shearing of the copper substrate. The goal of this project was to design a scraper which could remove the ablated aluminum without damaging the soft copper rail surface and increase the useful life of a set of railgun rails, decreasing the number of costly and time-consuming teardowns.

Since previous research did not exist on the topic, numerous materials were investigated for use as a high velocity scraper, however it was found that titanium Ti-6AL-4V had the best combination of conductivity, stiffness, strength, light weight, and fracture toughness to handle the immense forces within the railgun. A plow shaped tip was designed to attach to existing armature types. The combination was then tested on a set of rails with massive aluminum ablation and was shown to be a success after the rail returned to a favorable condition and excessive deposits were removed. After launching approximately 100 standard shots through the test gun, the scraper was fired, and results were observed to be acceptable. Future work will include improvements in armature manufacturability by utilizing selective laser sintering 3d printing technology.

Introduction

An electromagnetic launcher or railgun relies on the Lorenz force to accelerate projectiles known as armatures to high speeds along a pair of conductive rails. Due to the large current densities required to achieve the desired velocities, the armature experiences a tremendous amount of joule heating, vaporizing a portion of the armature at the contact points and coating the rails that guide its path (Cooper, 2007). This ablation impedes the performance of subsequent armatures, causing deformation and increasing the incidence of voltage spikes due to poor continuity (Stefani, 2001). One possible method for removing the ablated material from the rail system is periodically launching an armature with a titanium scraper attached to its fore end and shearing the deposits from the rails.

Over the course of three decades of development, this approach to grooming the rail topography has yet to be reported. However, many other aspects of the design have been perfected and established as standard practice. The use of C-shaped armatures with trailing legs that grip the rails using the Lorenz force was first realized in the late 1980's (Long, 1989). The use of convex rails is also a staple of modern railguns. The curved surfaces decrease the intensity of magnetic current spikes, known as the skin effect (Jin, 2014). Finally, the solid aluminum construction of the armature, combined with the tin-doped copper alloy of the rails, provides a combination that maximizes current transfer while limiting shear-induced tearing at the rail surface (Kesthkar, 2008).

This paper explores the effectiveness of a titanium scraper in removing aluminum ablation and other detritus from a railgun's rail surface. A simple plow-shaped titanium scraper design is considered and undergoes an electromagnetic current load test, which helps determine the correct thickness and profile to be used for the scraper, yielding promising results. The scraper is then fired over a set of well worn rails and the surfaces of the tests rails as well as the recovered scraper are analyzed for deformation and surface wear. If a functioning titanium scraper were to be developed, the operational costs of railguns would greatly decrease due to longer service intervals, less labor required to clean the weapons, and fewer rails consumed. This would increase the likelihood of operational use and widespread deployment.

Methods and Materials

In order to create a viable scraper for use in an electromagnetic railgun, the optimal material had to be selected. The material would need to be able to retain its geometry and material properties under the extreme joule heating present within the railgun. In addition, it would have to have as low a density as possible so as not to disrupt the dynamic stability of the armature. Additionally, the final weight of the armature with scraper attached had to be close enough to the weight of a virgin armature that the travel time within the gun was not drastically altered. This aspect of the design is critical because the capacitors driving the railgun have timings which correlate with a projected armature position within the gun. If the final combination were to be too light, the armature-plow hybrid would accelerate too rapidly and exit the gun before all capacitors had fired, which could lead to destruction of the weapon. If the armature-scraper combo were to be too heavy, the current concentrations between the rails may critically decay before the armature exits, leading to a low power shot. Having a scraper and armature combination which uses the same capacitor timings as a standard shot is key for ease of use in the field.

Second, the resistivity of the material had to be low enough that the properties of the scraper wouldn't be compromised during firing. Since 350,000 amps of current (Watt, 2007) can travel through the armature, a material with a high resistivity like stainless steel would simply soften and deform as it encounters the aluminum ablation in its path. Given the requirements, titanium was determined to be best suited for the task. **Figure 1** shows one of the many resources used to determine this.

With the material determined, an appropriate geometry had to be created which accounted for thermal expansion, armature rotation, and possible deformation of the scraper. To account for thermal expansion, the scraper was intentionally undersized .0005" vertically. It was calculated that an armature would expand approximately .001" upon assuming its final temperature of 455 ºC. The .0005" of interference remaining would allow the scraper to maintain bearing pressure on the rails as it moved down the length of the system. To account for armature rotation and deformation, the cutting head of the scraper was given a negative rake angle to avoid any possible gouging of the rail material as it traveled down the length of the gun. Preliminary calculations indicated that the greatest rotation could be no greater than 5 degrees so rake was set to 10 degrees using a safety factor of 2. The final armature design in shown in **Figure 2.**

To manufacture the scraper tipped armatures, a wire edm system was used to cut the scaper and the aluminum armature. The final product of this high precision manufacturing process is shown in **Figure 3**. A tolerance of .00001" was employed for this process to ensure the best results. Next two holes using 28 drill bits were drilled .354" apart into the frontal face of the armature. Two holes using 29 drill bits were then drilled .354" apart into the front face of the titanium scraper. The two holes in the armature were then tapped with a 5-40 NF tap and the scraper was attached with two 5-40 x .5" hex bolts.

To test the scraper, a set of rails was prepared by conducting a test series consisting of 100 shots fired at 4 kV per capacitor using the test setup shown in **Figure 4.** Each armature had a target mass of 9.8 grams. Test shots were conducted with ample time separation to minimize thermal effects and warping on the rail system. After the test shots were conducted the rails were removed and inspected as shown in **Figure 5**. Notable topographical features were recorded and then the rails were placed on the measurement setup shown in **Figure 6** and location marks were struck 1 cm apart beginning at the startup region and extending 50 cm until well after the transition region. The rails were then mounted in a vise and thickness was measured at each tick mark using a Starrett distance gage as shown in **Figure 7**.

After preliminary measurements were conducted, the gun was carefully rebuilt with the rails mounted within the containment. The disassembled gun with bottom rail placed for reassembly is shown in **Figure 8.** Five shots were fired to reseat the rails and then the completed scraper was fired. The gun was once again disassembled, and the thickness of the rails were recorded.

Results

The scraper attached to the armature without incident and remained attached while it travelled down the barrel of the gun, removing a consistent amount of ablation throughout its travel as shown in **Figure 9** and **Figure 10** corresponding to the top and bottom rails, respectively. The scraper dulled the peaks in the ablation and filled in the valleys, helping to improve surface finish as well. At no point through the distance of the barrel did the scraper mar the copper surface of the rails. In **Figure 11,** a particularly nasty dip in the ablation (previously noted in **Figure 5)** is shown to be partially filled in with aluminum, proving that the scraper greatly improved the surface quality of the set of rails.

Figure 12 shows another view of the rail surface after being fired from the gun. This view shows the center of the transition region where the scraper partially cleaned the ablation off of the rail down to the copper substrate. Given the fact that cracking can be noted in the region of heaviest ablation, it is likely that the irregular pressure applied by the scraper separated the ablation from the rail surface. This cracked ablation would likely break off of the rail surface in subsequent shots.

Conclusion and Future Work

The physical removal of ablation from the rails of an electromagnetic railgun is an offers promise in prolonging the useful life of a set of railgun rails, increasing service intervals and decreasing the labor required to operate the weapon system. The titanium scraper used in this test was able to effectively smooth and remove surface ablation from a heavily worn set of rails. The scraper was easily fired using the same parameters as a virgin armature, was as easy to load as a virgin armature, and was able to remove several thousandths of ablation while filling in low points as well. In addition, the scraper was able to complete its task without marring the underlying copper or getting stuck within the system. Overall, the scraper proved to be a success, such that a 1000 shot test series is warranted, and will be conducted to validate the effectiveness of the scraper in improving the long-term reliability of a railgun.

Appendix

Metal	k W/mK	ρ $10^{-8}\Omega m$	$k \cdot \rho$ $10^{-8} W\Omega/K$	k/ρ $10^{8} W/m^2\Omega K$	α $10^{-3}K^{-1}$
Ag	427	1.6	683	266.9	3.8
Al	226	2.8	633	80.7	4.5
Alumel	31	30	930	1.0	1.9
Au	318	2.4	763	132.5	3.7
Chromel	20	71	1420	0.3	0.3
Co	100	6.3	630	15.9	6.6
Constantan	25	50	1250	0.5	0.0
Cu	394	1.7	670	231.8	4.3
Inconel	15	100	1500	0.2	?
Manganin	22	45	990	0.5	0.0
Mo	140	6	840	23.3	4.4
Nb	91	6.9	628	13.2	2.6
Ni	90	7	630	12.9	6.8
NiCr	13.4	108	1447	0.1	0.4
Pa	72	10.8	778	6.7	4.2
Phosphorbronze	35	20.6	721	1.7	4.2
Pb	60	10	600	6.0	0.6
Pt	72	11	792	6.5	3.9
Pt90Ir10	31	25	775	1.2	1.3
Pt90Rh10	38	19	722	2.0	1.7
Stainless steel	16	70	1120	0.2	3.0
Ti	22	54	1188	0.4	3.8
V	36	19	684	1.9	3.9
W	170	6	1020	28.3	4.8
Zn	120	6	720	20.0	4.2

Figure 1 shows the electrical and thermal conductivities of various metals.

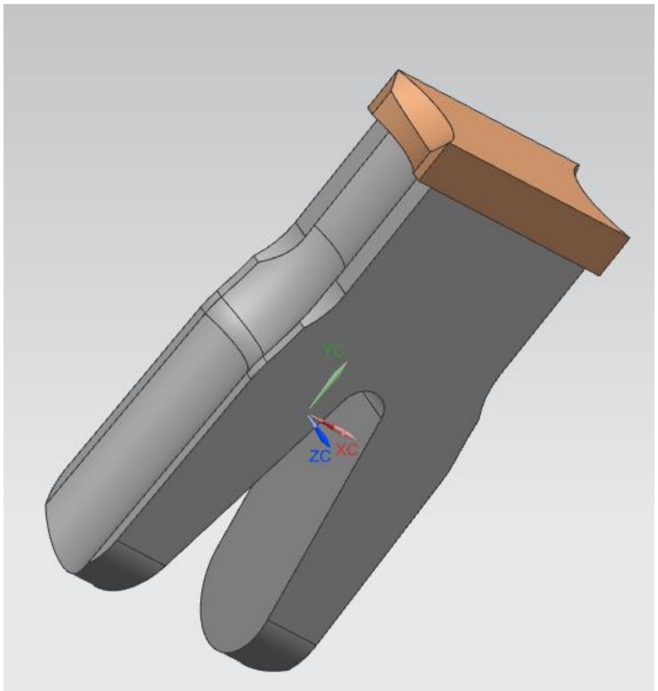

Figure 2 shows the final scraper design attached to an armature

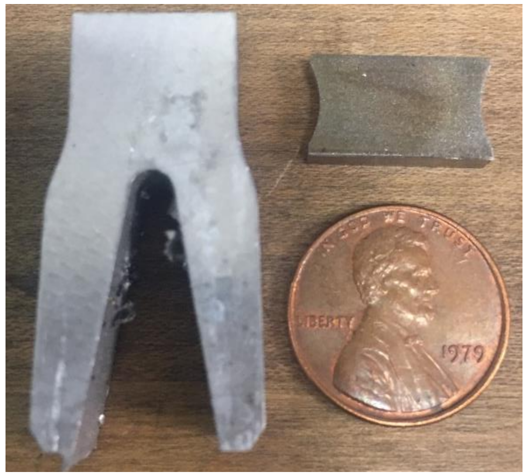

Figure 3 shows the finished armature and scraper freshly cut

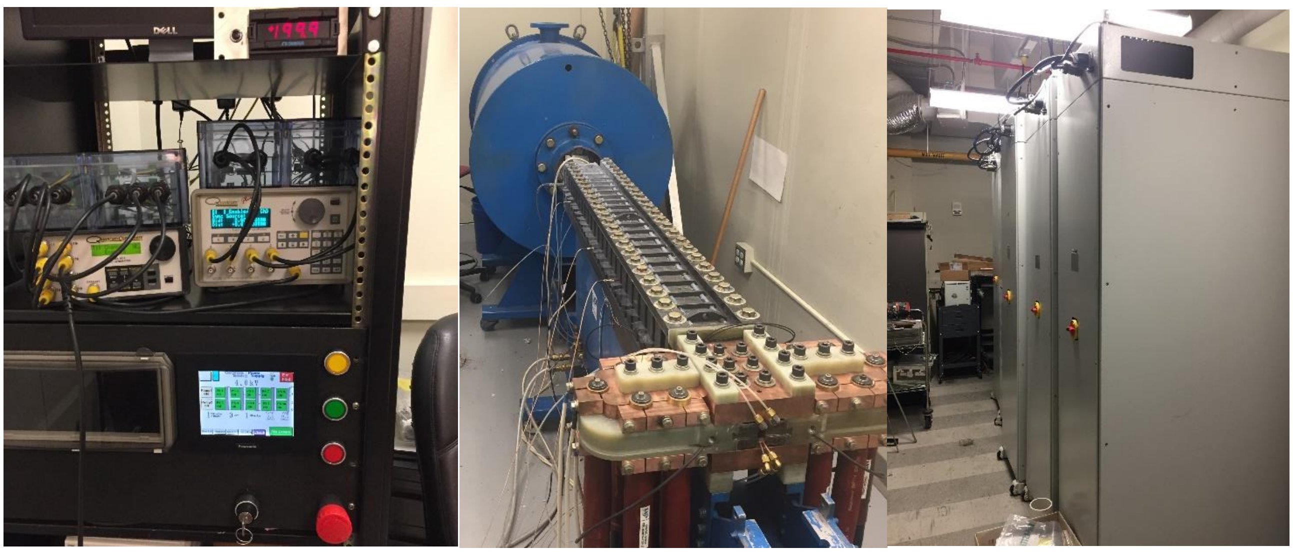

Figure 4 shows the test setup consisting of the control module, the railgun, and capacitor banks respectively

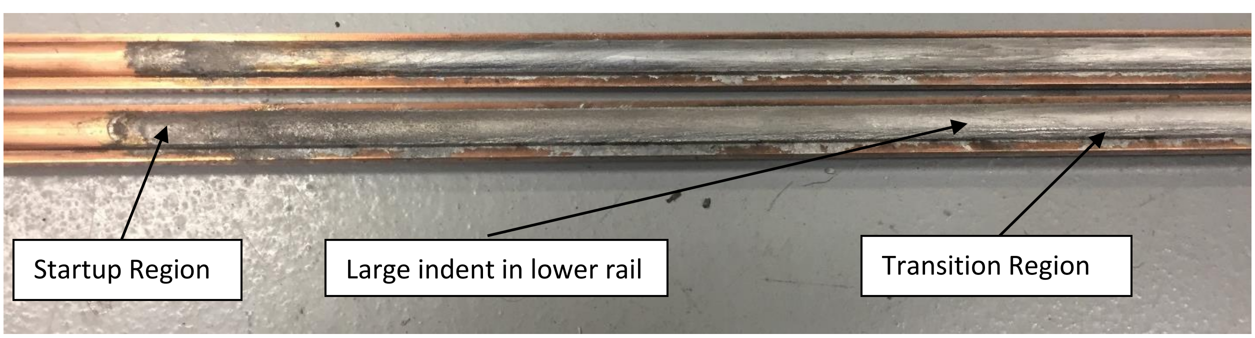

Figure 5 shows the ablation and wear caused by 100 test shots. The startup region experienced vaporization of the copper rail while the transition region experienced the most pronounced aluminum deposition.

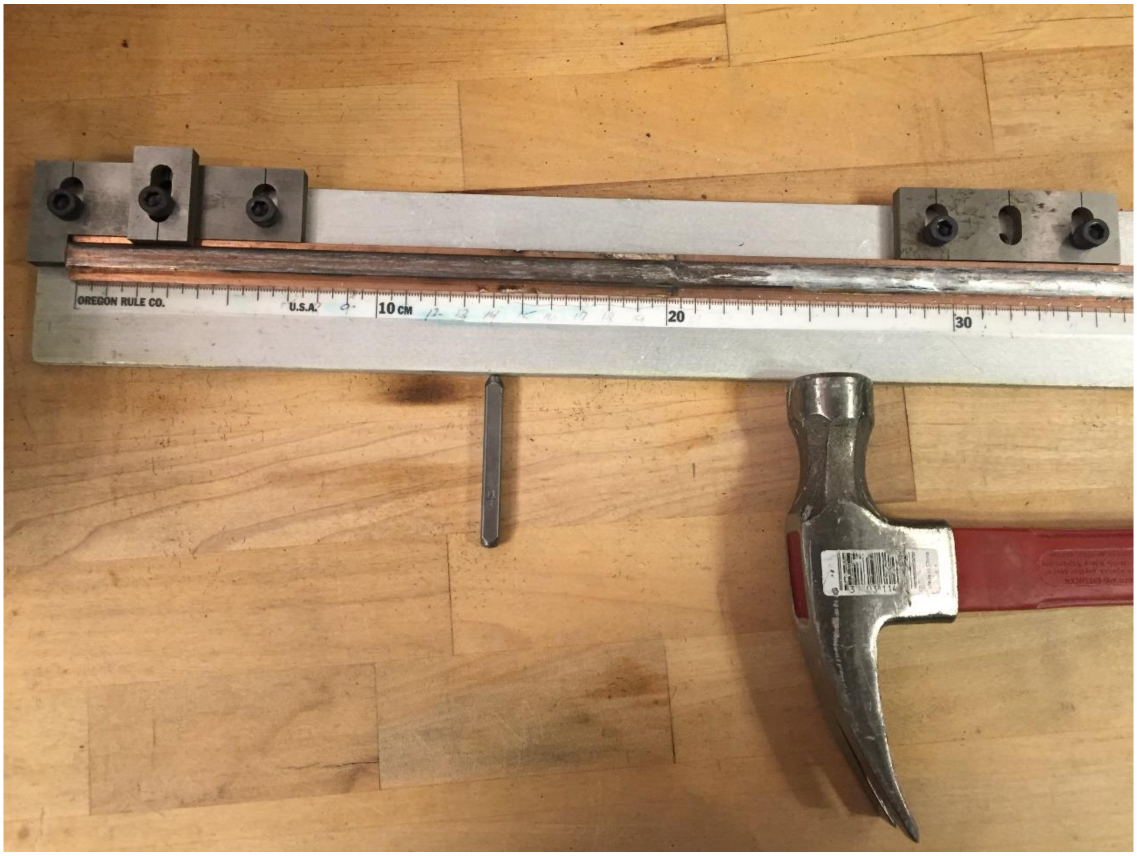

Figure 6 shows the measurements fixture, die, and hammer used to create the location marks

Figure 7 shows the Starrett distance gage and fixture used to measure rail thickness

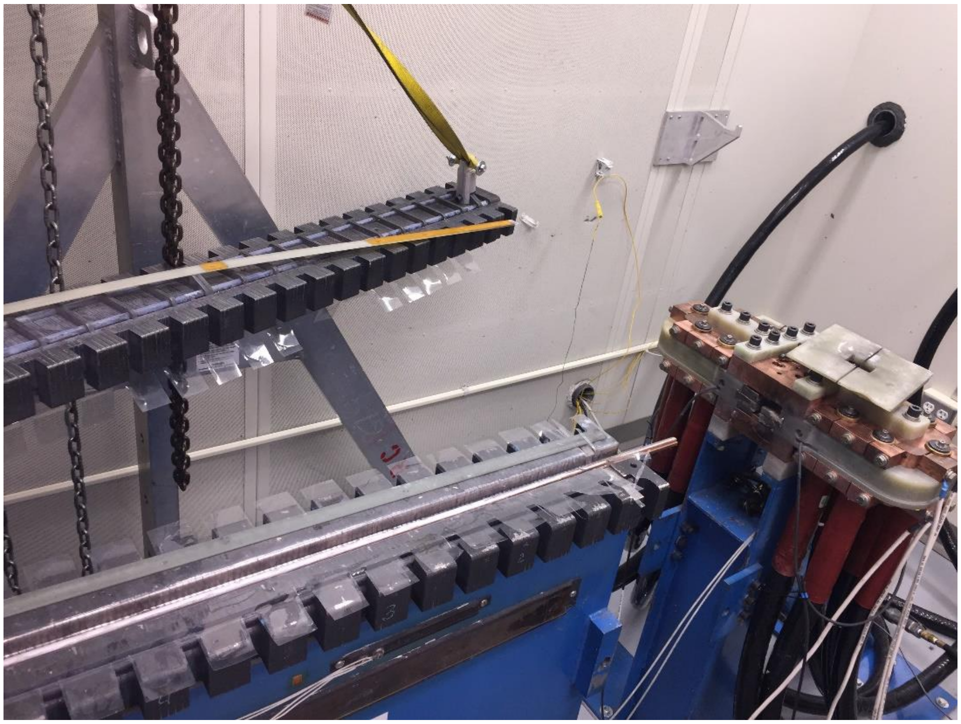

Figure 8 shows the disassembled gun with lower rail seated

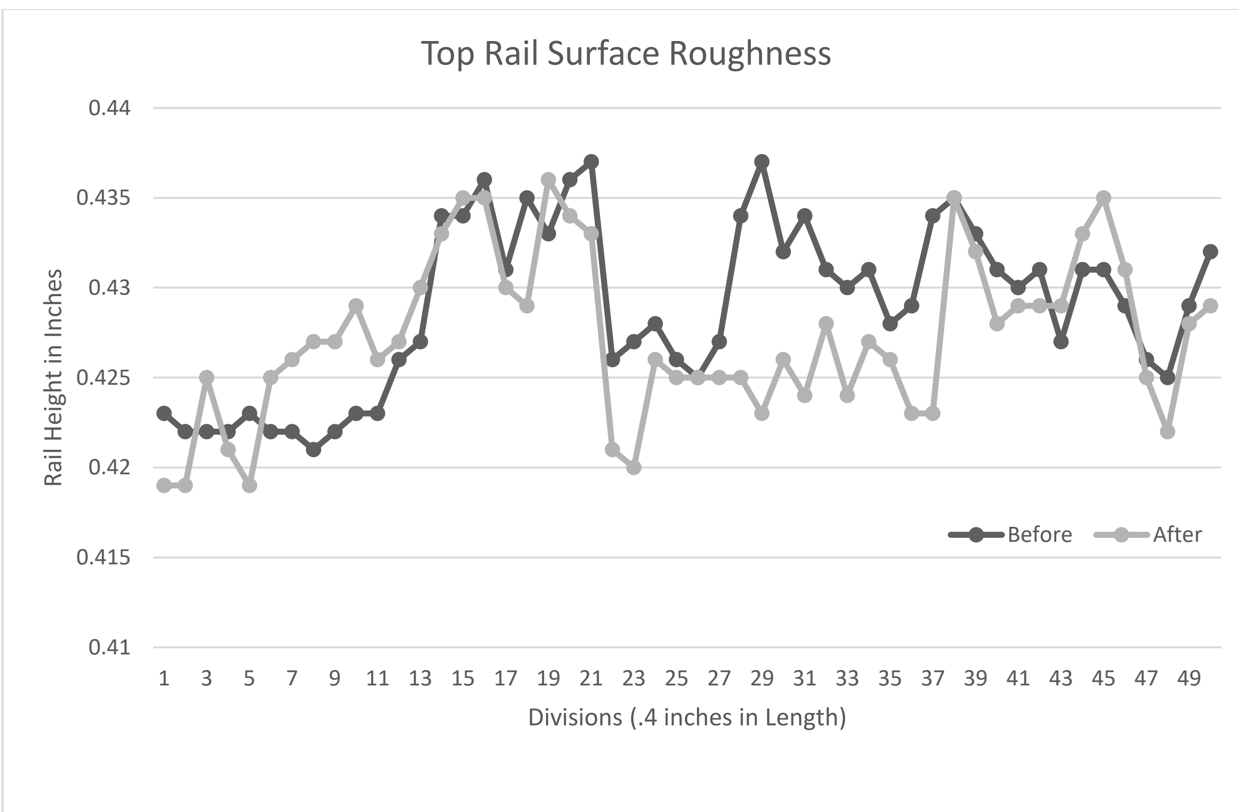

Figure 9 shows the surface roughness of the top rail before and after the scraper was fired

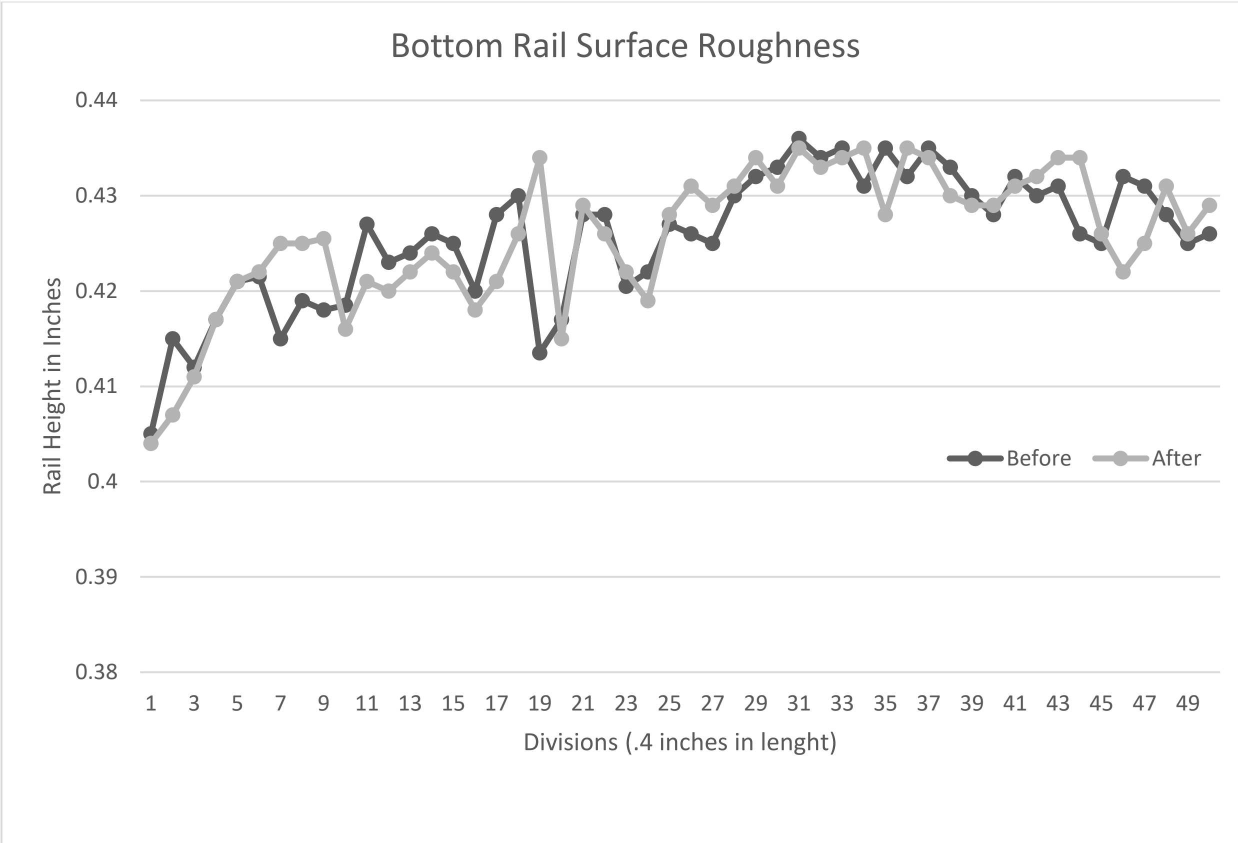

Figure 10 shows the surface roughness of the bottom rail before and after the scraper was fired.

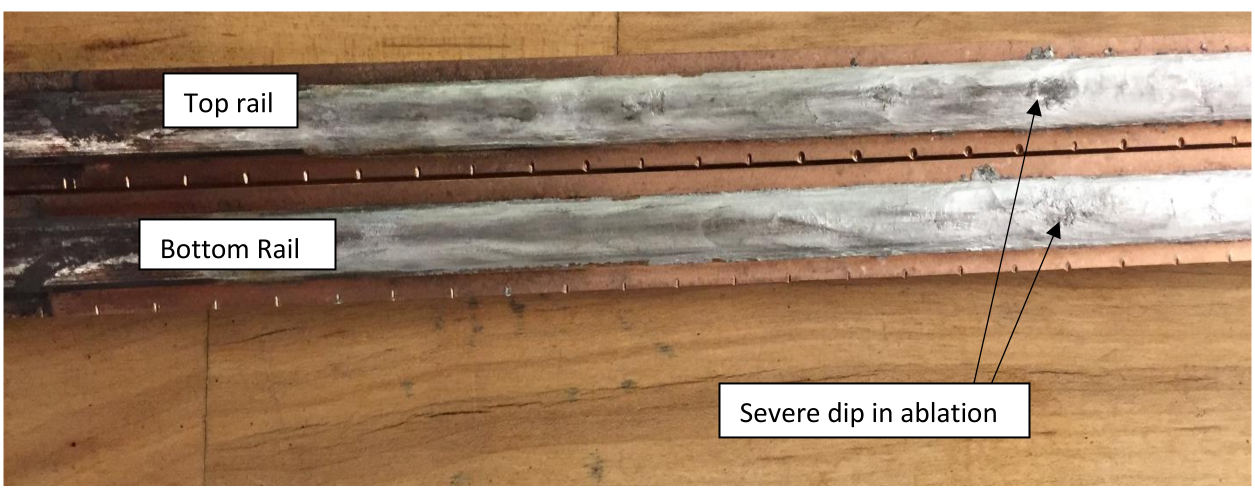

Figure 11 shows the rail surface after the scraper has been fired. The severe dip highlighted in the figure corresponds to division 19 on the x-axis Figure 9 and Figure 10.

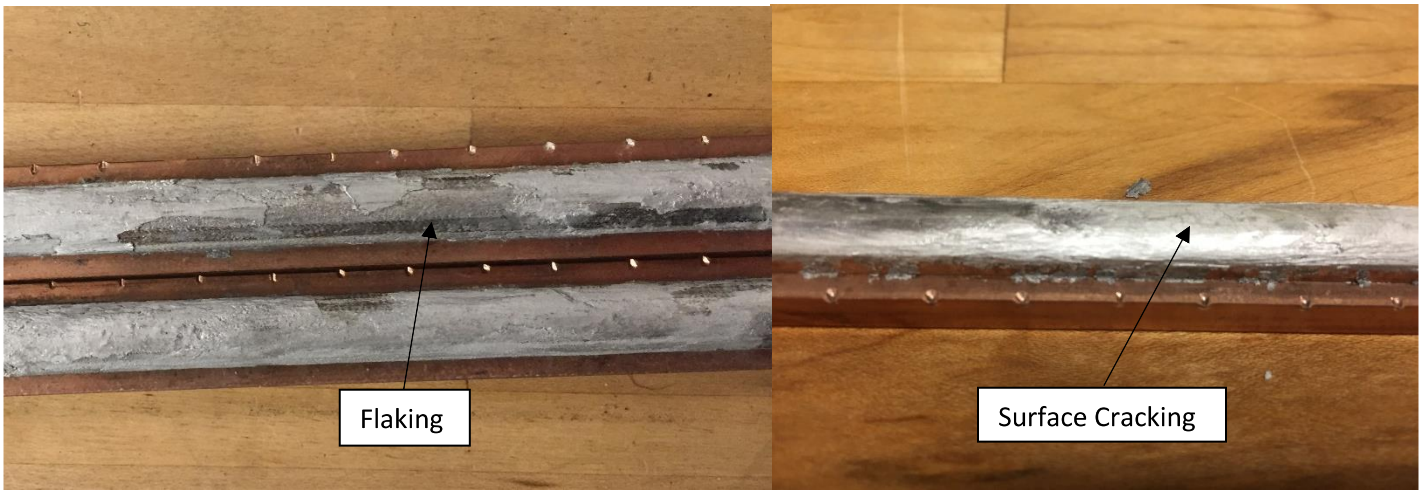

Figure 12 Shows flaking of aluminum ablation and cracking of ablation in the transition region

Citations

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